Societal Benefits of Earth System Science

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Abstract | Climate prediction over India is focused on the monsoons and has a history of well over a century. Weather forecast efforts span over 7 decades. As climate change issues take center stage, the need for a deeper understanding of the components of earth systems is recognized as critical for learning how the earth is changing. The long-term measurements, both in situ and satellite are crucial for improved predictive capability to forecast weather, climate and hazards. Capacity building in climate change research is also paramount for responsible stewardship of the Earth as an integrated and it is an investment that will pay dividends for generations to come. A number of programs focused on monsoons to earthquakes to energy and ecosystems are being planned to tackle these important issues. The success of these programs depends not only on technology and infrastructure but on people, an education system that produces the scientists and managers needed for implementing such an approach. We need to build effective communication with various stake-holders including policy-makers.

1. Introduction

The prediction of the weather, climate and hazards as societal benefit services has been well-recognized, Such services need a scientific understanding of the earth system (atmosphere, hydrosphere, cryosphere, geosphere and biosphere) in an integrated manner as well as a knowledge of how each component of the earth system responds to various natural processes and anthropogenic activities. The interaction between different components and how the earth is changing also provides a physical basis for studying climate variability and change. Thus, it is a science of national importance.

The national agenda for studying the earth system is to promote *discovery* to provide new perspective on earth processes, a better *understanding* of the interaction of various components of earth processes and an application of this knowledge for the sustainable use of earth resources. The pursuit of scientific questions or new phenomena, and exploration of new terrain is critical. The knowledge gained from such discovery and understanding of the eath system should be applied for public good.

The development of societal services depends on the following.

i. Long-term measurements of earth system variables to record vital signs of the earth system.
ii. Focused process studies and development of earth system models
iii. A robust earth information system and
iv. Development of web- and location-based services.

The Earth System Science Organization functions on a mission-mode and the major missions are as follows.

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i. Developing and improving capability to forecast weather, climate, and hazard related phenomena for societal, economic and environmental benefits.
ii. Understanding climate variability and change and developing climate services.
iii. Exploring ocean resources for socio-economic benefit.
iv. Developing state-of-the art technology for harnessing marine resources
v. Defining and deploying satellite-based, airborne- and in-situ atmospheric, ocean, polar and geosphere observing systems.

2. Weather prediction and services

The primary objectives are to provide current and forecast meteorological information for the optimum operation of weather-sensitive activities like agriculture, irrigation, shipping, aviation, sport, etc. These observations are critical and are currently being upgraded by adding 550 automatic weather stations(AWS), 1350 automatic rain gauges (ARG), Doppler weather radars (DWR), GPS-sonde, etc. Short-term (up to 3 days) and medium-range (up to 5–7 days) forecasts are being generated using numerical weather prediction models. A new high resolution GFS (Global Forecast System) based on the T382L64 model and its associated data assimilation including radiance assimilation has been made operational. This has significantly improved spatial resolution with an accuracy of 35 km. Besides, a meso-scale model WRF model (27 km) forecast was implemented in real time for the prediction of weather systems like tropical depressions, thunderstorms, etc. Very high resolution (9 km and 3 km) nested WRF runs have been done for exclusive case studies of severe weather. The accuracy obtained is about 70–75 per cent. Global model assimilation utilizing 4D VAR is being done on an experimental basis.

Another important component is the development of an end-to-end forecasting system that connects the various instruments and observing systems, their real time transmission and linkage to a central data processing system, and their utilization in numerical models, thus providing a state-of-the-art IT-based forecasting environment to all forecasters throughout the country. This involves integrating all observations and overlaying them on model outputs and synoptic charts along with proper visualization and dissemination of weather forecasts to the end users

The Seasonal forecast of the monsoon is a major challenge. It has been observed that the skill of numerical models do not provide consistent results (Table 1). In view of this, a statistical approach has been followed, which provides a reasonable forecast. However, it has been observed that extreme conditions are not well captured. Further improvement in numerical weather modeling and assimilation techniques will certainly improve forecasts.

Predicting breaks during the monsoon is vital. Monsoon droughts are dominated by "prolonged breaks" in rainfall on the sub-seasonal time-scale. Internal feedbacks between the monsoon and mid-latitude circulation anomalies need to be understood.

The following activities have been initiated to improve forecasts.

i. Understanding of Processes: Monsoon variability and predictability: Impact of IOD & ENSO, active/break spell, cloud microphysics, cloud aerosol interaction, etc.
ii. Augmenting Observing System: AWS, ARG, DWR, GPS sonde, wind profiles, etc. to be augmented by 2012. OCEANSAT II Ocean Colour Monitor (OCM) and scatterometer data to be made available shortly. INSAT 3D, Meghatropique to be launched shortly.
iii. Computing System: Computing resources of about 120 teraflops have been deployed. This will be increased to 700 teraflops.
iv. Analysis and Modeling: Assimilation of satellite radiances and DWR data, development of coupled models and high-resolution regional models are under way.
v. Development of Human Resources: An advanced training school on Earth Systems and Climate Change has been set up and will start functioning from June 2011.

2.1. *Agromet services*

About 60 per cent of the population depends on agriculture and thus weather-based agricultural advisories are critical. Short-term predictions of rainfall, maximum and minimum temperature, total cloud cover, surface relative humidity and wind, based on the Multi-Model Ensemble (MME) having a 35 km grid for 130 Agromet field units are routinely generated. Based on these predictions from agricultural scientists, these advisories provide information on suitable times for sowing crops, need-based application of fertilisers, pesticides, insecticides, efficient irrigation and harvest. Bi-weekly bulletins for more than 575 districts have been issued for farmers. Such bulletins for each state and country have also been generated for policy decisions. These advisories are disseminated through print, electronic media and multilingual Web portals. The development of location-based services through mobiles has been very successful, and about 450,000 farmers utilize this service by paying an annual subscription. It is expected that 2 million farmers will subscribe to this service by 2011.

Table 1: Seasonal Monsoon Forecasts.

Institutes	2005	2006	2007	2008	2009	2010
UK Met (J)	Normal to Below N.	Normal to Above N.	Normal to Above N.	Normal to Above N.	—	—
ECMWF (J)	Above N.	Normal to Below N.	Above N.	Normal	Normal to Above N.	Above N.
IRI MME (J)	No signal	No Signal	Above N.	No signal	No signal	Normal to Above N.
NCEP (J)	Above N.	Above N.	Above N.	Above N.	—	—
ECPC, USA (J)	—	Below N.	Normal to Below N.	Normal	—	—
WMO LC MME (J)	—	—	—	—	Normal to Above N.	Normal to Above N.
APEC, Climate Center	—	—	—	—	Normal to Above N.	Normal to Above N.
IMD (A, J)	98, 98%	93, 92%	95, 93%	99, 100%	96, 93, 87%	98, 102%
Actual	99%	100%	106%	98%	78%	102%

2.2. *Aviation services – Fog forecast*

Fog affects aviation services severely during winters. The monitoring, forecasting and dissemination of the intensity and duration of the fog is crucial. Runway Visibility Recorders (RVRs) provide visibility conditions along all runways. Met Reports (forecast of met conditions for 9 to 30 hours) every 30 minutes, fog forecasts for the next 6 hours and the outlook for the next 12 hours are provided. Trend Forecasts for the next 2 hours have been introduced. Information is provided through websites, SMS, IVRS, phone, fax, etc. The accuracy of the forecast was 94 and 86 % for December and January (2009–10), respectively, substantially improved from the 2008–09 (74 and 58 % for December and January, resp.) winter.

2.3. *Hydrological service*

Based on real-time daily rainfall data, weekly district-wise, sub-division-wise and state-wise, season-wise rainfall distribution summaries are prepared in the form of rainfall tables and maps. These rainfall statistics provide information useful to agricultural scientists, planners and decision makers. The inputs on rainfall intensity and distribution are provided to the Central Water Commission (CWC) through 10 Flood Meteorological Offices (FMOs) for operational flood forecasting. Design storm estimates (rainfall magnitude and time distribution) for various river catchments/ projects in the country have been computed by engineers in estimating design flood for hydraulic structures, irrigation projects, dams, etc.

2.4. *Environmental service*

A network for air pollution monitoring stations has been set up at Allahabad, Jodhpur, Kodaikanal, Minicoy, Mohanbari, Nagpur, Port Blair, Pune, Srinagar and Visakhapatnam to collect rain samples for chemical analysis and measurement of atmospheric turbidity with the objective of documenting the long-term changes in the composition of trace species of the atmosphere. These data provides useful and reliable long-term observations of the chemical composition of the atmosphere and related parameters.

Specific services pertaining to the assessment of likely air pollution impacts arising from thermal power generation, industries and mining activities have also been provided. Atmospheric diffusion models developed for carrying out air quality impacts of multiple sources located in different climatic and geographical conditions are being utilized for site-selection of industries and adoption of air pollution control strategies.

The System of Air Quality Forecasting and Research (SAFAR) for Air Quality Forecasting for the Commonwealth Games (CWG) has been accomplished for the first time in India along with establishing forecasts and a now-casting system for the Games through the commissioning of AWS, DWR and other observing systems that will provide forecast products specific to venues.

3. Ocean information and services

Life originated in the ocean and it is the ocean that makes planet earth habitable. This is why we focus our attention on the health of the ocean. Oceans have been providing food, energy, recreation and means for transportation. Sustained and systematic observation and information about oceans, especially for physical, biogeochemical, biological and ecological parameters, are needed. An integrated observing system, including remote sensing and in situ, is crucial. The collection of such data requires large investments in satellites, research vessels, moored buoys and autonomous vehicles for observing and sampling water columns.

India has a reasonably adequate ocean observing system which includes moored buoys, drifting buoys, wave recorders, current meter moorings and Argo floats. OCEANSAT II is expected to provide ocean colour and scatterometer wind data routinely. Apart from this, data from international satellites also provide data on the Indian Ocean. Large amounts of data from satellite and in situ platforms have been organized and web-based data services are available.

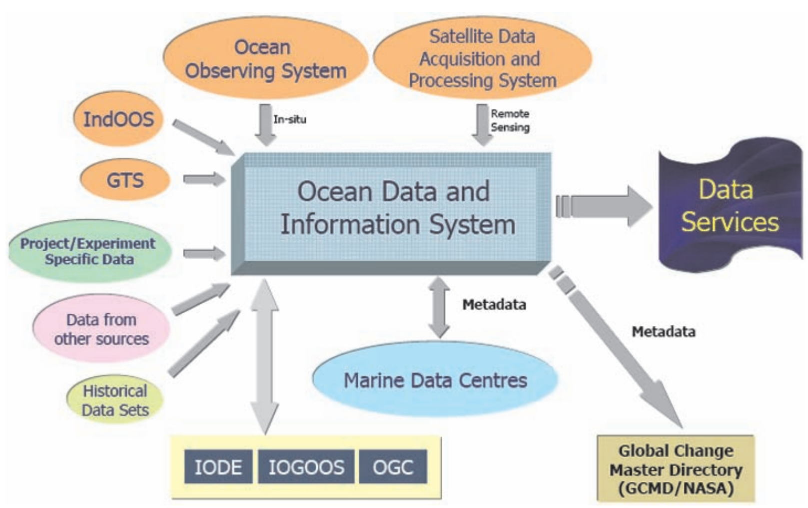
The Ocean Data and Information System (ODIS) provides data and information on the physical, chemical and biological parameters of the ocean and coasts in various spatial and temporal domains. It is end-to-end ocean data management system, developed by exploiting advances in the field of information and communication technology that has brought about revolutionary changes in data acquisition, processing, analysis and data availability (Fig. 1). ODIS is fed by voluminous (~5 Tb per year) and highly heterogeneous oceanographic data in real time, acquired from ocean observing systems (both in-situ and remote sensing) established in the Indian Ocean. The challenges involved in developing ODIS are the integration of heterogeneous data received from a wide variety of ocean observing systems, generation of metadata, quality control, generation of database and implementation of data warehousing and mining concepts for providing web-based data services. ODIS forms a vital component for providing web-based services. The web-site has become a prime vehicle for providing ocean data, information and advisory services such as potential fishing zones, ocean state forecasts, Indian Argo, Indian Ocean Global Ocean Observing System, etc. The web-based online delivery system provides the user with multi-lingual and Web-GIS capabilities to query, analyze, visualize and download ocean data, and information and advisory services at different spatial and temporal resolutions.

3.1. *Fishery advisory*

About 7 million people living along the Indian coastline, which spans more than 7500 km, are dependent on fishing for their livelihood. Only 15% of total fish production is from aquaculture; hence we continue to depend on capture fishery. Locating and catching fish is challenging as fish stocks dwindle and move further offshore, thus increasing the search time, cost and effort. Reliable and timely forecasts on the potential zones of fish aggregation help to reduce the time and effort spent in searching the fishing grounds for the socio-economic benefit of the fishing community.

Fishes are known to react to changes in the surrounding environment and migrate to areas where favorable conditions in terms of seawater temperature, salinity, colour, visibility, dissolved oxygen levels, etc., exist. Sea Surface Temperature (SST), the indicative parameter of the environment,

Figure 1: Elements of Ocean data and information system.



is most easily observed on satellite images. The availability of food is an important factor which controls their occurrence, abundance and migration in the sea. Chlorophyll-a is the indicator of the availability of food for fish.

These forecasts are routinely given thrice-a-week and are valid for a period of three days along with the ocean state forecast. These advisories are given in nine local languages and English through the web, e-mail, fax, radio and TV as well as electronic display boards in fishing harbours and information kiosks. It has been estimated that 40,000 fishermen use these advisories. It saves a lot of fuel and time (60–70 per cent) and thus allows for efficient fishing. It has been estimated that the success rate is around ~80 %.

3.2. *Ocean Colour Products*

Chlorophyll plays an important role in the ocean's biological productivity and its impact on climate. Hence answers are required for the following:

i. How much phytoplankton the oceans contain
ii. Where they are located
iii. How their distribution changes with time
iv. How much photosynthesis they perform

Ocean colour products, chlorophyll *a*, sea surface temperatures, attenuation coefficients and suspended sediments are generated routinely and weekly and monthly products are made to answer the questions raised above.

3.3. *Ocean state forecasting*

Efforts to develop real-time forecasts for the Indian Ocean using numerical models are at the initial stage. The Indian Ocean Forecasting System (INDOFOS) includes forecasts of ocean wave height, wave direction, sea surface temperature (SST), surface currents, mixed layer depth (MLD) and depth of 20°C isotherm for the next five days at six hourly intervals (Fig. 2). The beneficiaries of INDOFOS are traditional and mechanized fishermen, the maritime boards, the Indian Navy, the Coast Guard, shipping companies and petroleum industries, energy industries and academic institutions. Location-specific models for wave forecasts for Gujarat, Maharashtra, Karnataka, Pondicherry have been set up. These products are extensively used by port authorities.

4. Disaster support

4.1. *Cyclone*

There has been significant improvement in the forecast of cyclones and this has been achieved primarily due to the implementation of high resolution models and an enhanced capability of acquiring atmospheric and ocean data. The cyclone track and intensity predictions are provided every six hours. The current error of 24 h track and the landfall forecast error is about 140 and 80 km, respectively. It is believed that cyclones are likely to increase in intensity and frequency. In view of this, there is a need to improve the prediction of track and landfall points and intensity. The prediction of rainfall, wind velocity, surge and inundation areas is a major challenge. This can be achieved through improved scientific understanding of physical processes, enhanced observation networks (Buoys, satellite, Radar and AWS) and improved modeling techniques through collaborative research.

4.2. *Earthquakes*

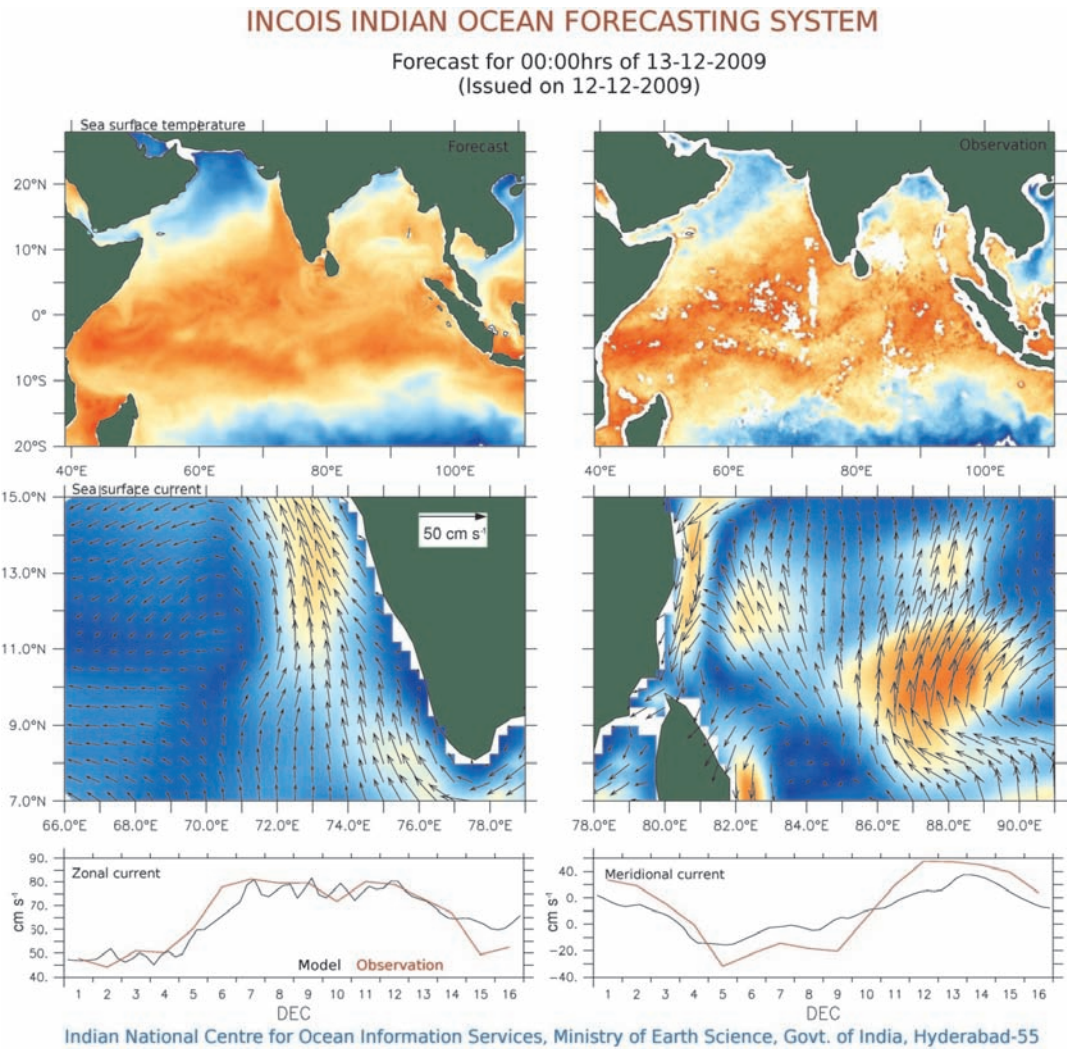
An optimum seismic network has been built in the country to provide information about earthquake magnitudes and locations in near real time The first information about an earthquake is provided within five minutes to all concerned .The density of seismic stations needs to be increased to be able to capture earthquakes of lower magnitude, which are required for precursor studies, and more detailed reports on vulnerable zones.

Earthquake predictions are currently not possible. However, we need to study various precursors of earthquakes to improve our understanding of earthquake processes. Various initiatives have been taken in this regard and are given below.

i. Monitoring of geochemical precursors including He, Ra, CO_2, CH_4 and water level changes , etc. in the A&N region, NW & NE Himalayas.
ii. EM & ionospheric precursory studies in Koyna, and Agra.
iii. High precision leveling, gravity and magnetic observations and crustal deformation using GPS in Uttaranchal and the NE Himalayan region
iv. Thermal precursory studies.
v. Measurement of strain levels in selected locations.
vi. SODAR (Sound Detection and Ranging) related studies along the entire Himalayan range.

About 500 towns and cities are vulnerable to earthquakes in India. Microzonation of these cities and towns have been undertaken to identify vulnerable areas. Small units of likely uniform hazard levels , based on geological, geotechnical, seismological and engineering parameters, have been delineated. The first level of microzonation of the National Capital Region, Jabalpur, Sikkim, Bangalore and Guwahati were completed at 1:50,000/1:25,000 scale. It is also important to conduct a geo-technical evaluation of vulnerability at map scales of 1:10,000 for important towns/cities with high risk, and to redefine building bye-laws.

Figure 2: Validation of sea surface temperature (top) and currents(bottom) from forecasts using a numerical ocean model.



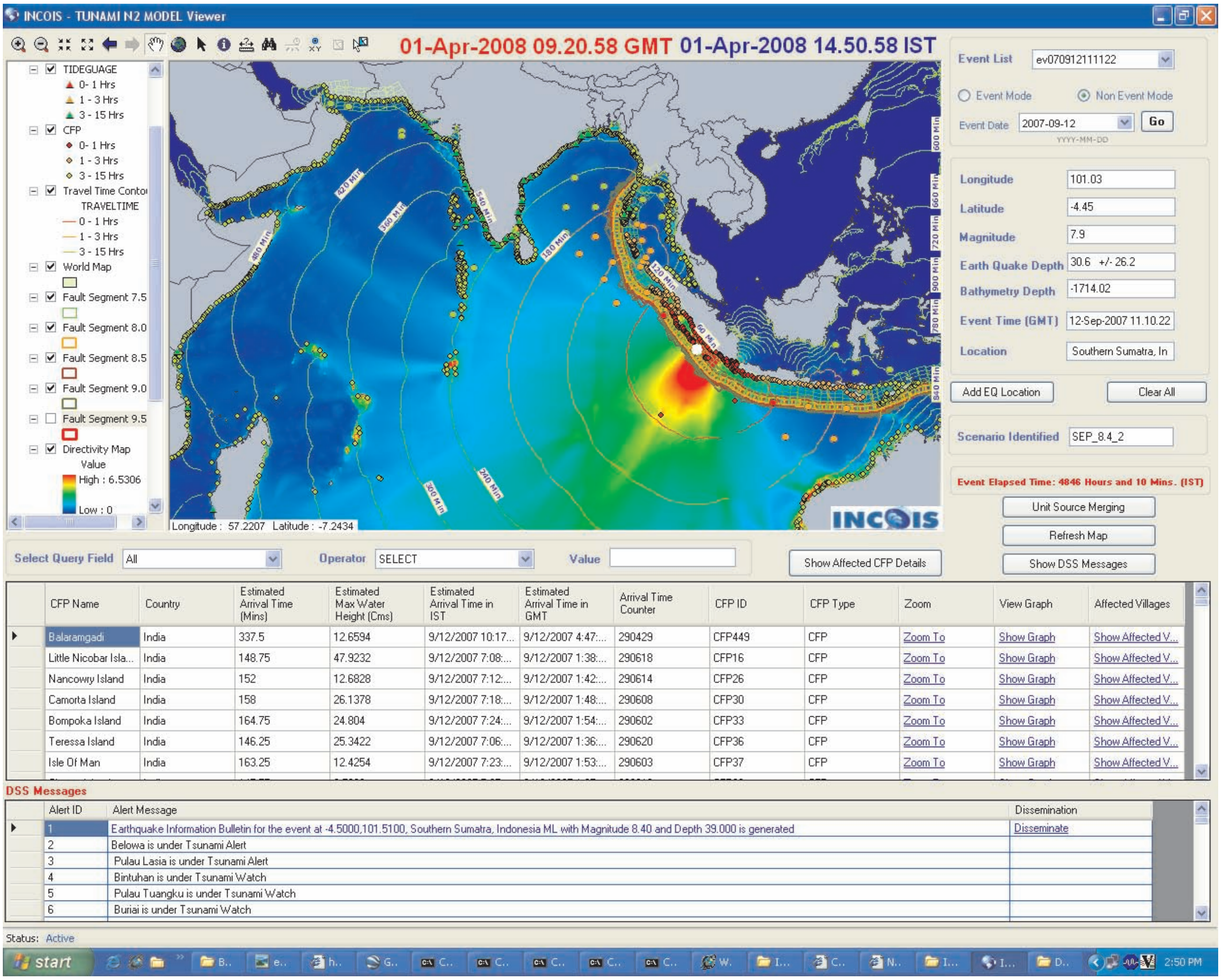
4.3. *Tsunami*

A Tsunami is a system of ocean gravity waves formed as a result of large-scale disturbances of the sea floor in a relatively short time. The Indian Ocean is likely to be affected by tsunamis generated mainly by earthquakes from the two potential source regions, the Andaman–Nicobar–Sumatra Island Arc and the Makran Subduction Zone. The reception of real-time data from a network of seismic and sea-level stations, analysis and display of the data, decision support systems, and mechanisms for the timely delivery of information have been established for the detection of tsunamis and fore-warning. For operational early warning, a large spatial database of pre-run numerical simulations has been created that can be accessed at the time of an earthquake event to generate a forecast of tsunami travel time and run up estimates for 1800 forecast points along the coast of the Indian Ocean (Fig. 3).

Satellite-based GPS can determine whether an earthquake is big enough to generate an ocean-wide tsunami. Current methods of earthquake estimation generally underestimate large earthquakes (>8.5). Methods of analysing GPS data quickly and accurately to assess the true potential of earthquakes are under way.

Tsunami run-up, storm surges, high waves, and sea-level-rise also cause the flooding of seawater into the land up to a few km resulting in the loss of human life and damage to property. To minimise such losses, coastal vulnerability maps have been prepared indicating the areas likely to be affected due to flooding. Inundation modelling uses high-resolution coastal topographic data

Figure 3: The TSUNAMI N2 model is customized for the Indian Ocean region Travel times, directivity maps, surge heights and the extent of inundation are given. A large database of scenarios for different magnitudes (6.5, 7.0, 7.5, 8.0, 8.5, 9.0 & 9.5) and depths (10, 20, 40, 60, 80 & 100 km) for a 100 x 50 km grid has been generated. A Forecast is given for 1800 coastal forecast points.



derived from CARTOSAT and aerial data. These maps are to be used by the central and state administration responsible for disaster management (Fig. 4). These community-level inundation maps are extremely useful for assessing the population and infrastructure at risk. High resolution 3D-GIS mapping has been done for some vulnerable areas of the Indian coastline.

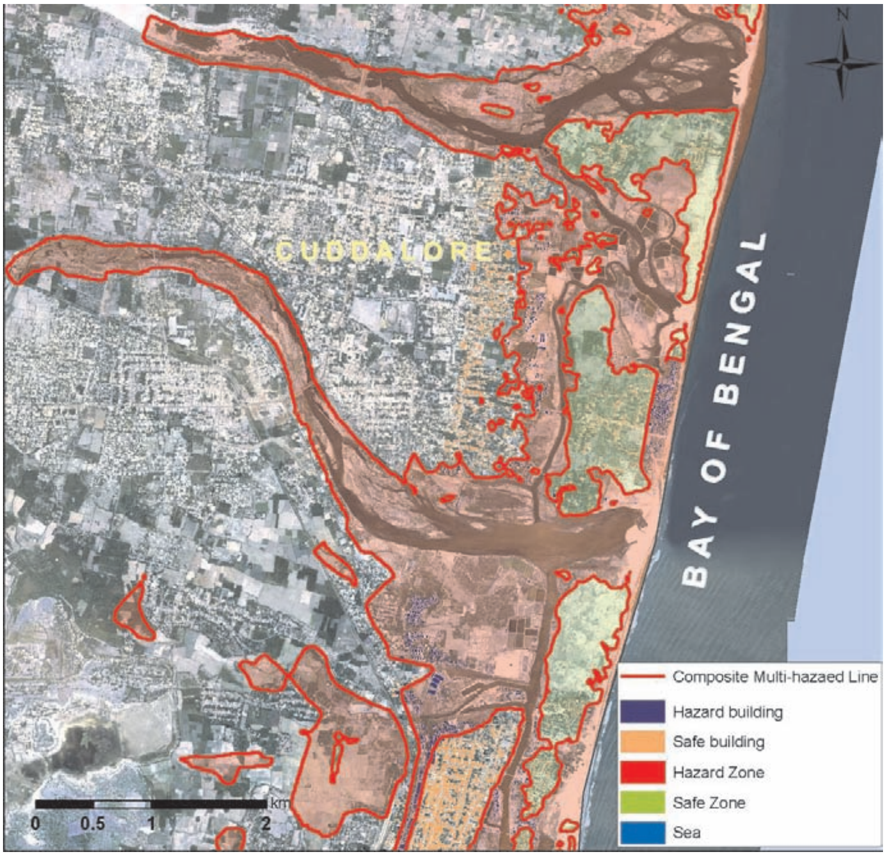
4.4. *Coastal erosion*

Coastal areas along the Indian coast experienced erosion due to extreme waves, deficient sediment supply, sea level rise and development of ports, etc. Coastal protection through revetments, groins, etc. without a thorough understanding of coastal processes will lead only to temporary solutions. Various engineering solutions have been demonstrated based on mathematical modeling. Baseline data on close-grid bathymetry, shoreline configuration, wave, tide and currents have been collected for use in such models. In Most places, low crested offshore structures (LCS) have been provided as solutions.

5. Ocean mineral resources

India has an Exclusive Economic Zone of 2 million sq km. A detailed geophysical and bathymetric survey has been undertaken for the exploration and assessment of mineral resources. In future, we are going to be more dependent on oceans as resources on land are dwindling.

Figure 4: A Multi-hazard Vulnerability map along Cuddalore, Tamil Nadu.



5.1. *Hydrothermal sulphides and cobalt crust*

The characterization of the slow spreading of the Carlsberg ridge, and the Andaman Subduction zone. in terms of tectonic, volcanic and hydrothermal processes is being investigated for hydrothermal sulphide deposits. The zones of hydrothermal mineralization and their relation with seafloor and sub seafloor ecosystems are being investigated. Cobalt-enriched ferromanganese crusts have been identified on the Afanasiy-Nikitin Seamount. The assessment of the resource potential of Co-rich deposits is continuining.

5.2. *Polymetallic nodules*

In search of polymetallic nodules, the survey and exploration of 4 million sq km was undertaken using single and multi-beam echo-sounding, magnetic and gravity surveys, and deep tow photography. This was one of the largest surveys ever undertaken. Sediment cores were collected from 250 locations and nodule samples were collected from 2500 locations. A Detailed chemical analysis of all samples revealed the presence of manganese, nickel, copper and cobalt. The total reserves are 380 million metric tons.

5.3. *Gas hydrate*

Gas hydrate is likely to provide energy in the near future. India has large reserves of gas hydrates. Geological surveys, swath bathymetry, deep tow side scans, multi-channel seismic surveys, ocean bottom seismic data collection, heat flow measurements have been conducted in the Bay of Bengal to assess the reserves of gas hydrate.

5.4. *Legal continental shelf survey*

The Exclusive Economic Zone (EEZ) extends up to 200 nautical miles. Under the Law of the Sea, the zone can be extended up to 350 nautical miles if a certain thickness of sediment prevails in the sea. A bathymetric, seismic, gravitational and magnetic survey of 31,000 line km was undertaken and 100 ocean bottom seismometers were deployed. These data have been organized in a data base and various outputs have been generated to claim additional areas under the EEZ.

6. Ocean technology

The main goal is to develop reliable indigenous technology for the harnessing of non-living and living resources. The major focus is on the development of technology related to the country's needs in the field of deep-sea mining, ocean energy, marine instrumentation, materials development, oceanic data collecting devices and observation systems, etc.

6.1. *Low Temperature Thermal Desalination*

To alleviate the problem of drinking water in coastal regions and islands, a initiative to develop Low Temperature Thermal Desalination (LTTD) technology to generate fresh water from sea water has been undertaken. A LTTD plant of 1 lakh liter per day capacity has been set up at Kavaratti, an island of Lakshadweep and has been working continuously. 3 more plants will be ready by 2012. Power plants generate a lot of hot water which is discharged into the sea. This water can be utilized to generate drinking water. A plant has been set up at the North Chennai Power Station utilizing the 1 lakh Liter/day plant for demonstration of the process.

6.2. *Mining Technology*

India has been planning to harness ocean mineral resources. this requires, the development of a set of three pieces of equipment, viz., In-situ soil tester, remotely operable vehicles (ROV), and a deep sea crawler. The In situ-soil tester measures sea bed soil properties and has been successfully tested at a depth of 5200 m in the Central Indian Ocean Basin (CIOB). The Deep water trials of the ROV were conducted successfully for the integration and testing of launching and recovery systems at a depth of 5000 m in the CIOB (Fig. 6). Complete hardware and software for the instrumentation and control systems were developed indigenously. The crawler to collect nodules has been tested at a depth of 450 m off the Malvan coast.

A coring system with 100 m core collecting capability up to a 3000 m water depth has been developed. Demonstration trials are currently underway. This equipment is being developed as a part of technology development for harnessing Gas Hydrate.

6.3. *Hatchery technology*

The development of hatchery technology of commercially important species is a major area for the providing alternate employment to fishermen. Production has taken place in Black lip pearl oysters at the Andaman hatchery. Breeding and rearing technology for marine ornamental fishes, viz. eight species of clown fishes and ten species of Damsel fishes has been perfected. Techniques for captive breeding, larval development and the mass culture of juveniles on four species of gastropods have been perfected. The Technology has been transferred to local fishermen.

6.4. *Fattening of lobsters and mud crabs*

A viable technology for fattening lobsters and mud crabs in cages was successfully developed and disseminated to beneficiaries in the Gulf of Mannar in Tamil Nadu and the Andaman & Nicobar Islands, on an experimental basis. There has been a substantial improvement in the earnings of coastal fishermen due to the implementation of this scheme.

7. Polar science

The mission is to plan, promote, co-ordinate and execute the entire gamut of polar science and logistic activities of the country in order to ensure the perceptible presence of India in Antarctica and to uphold our strategic interests in the southern continent and the surrounding oceans. India has sent thirty expeditions to Antarctica. The Maitri Station provides all the necessary facilities to conduct experiments in the field of atmospheric science, geology, geophysics, biology and glaciology. The monitoring of glaciers and the study of ice cores are major activities. It was observed that the temperature rose about 0.1°C during the last 100 years (Fig. 5). The Dakshin Gangotri glacier is retreating but its both banks show different degrees of magnitude of retreat (Fig. 6).

A Third station is being established in the Larsmann Hills. Studies accomplished in the

Figure 5: Increase in temperature in Antarctica.

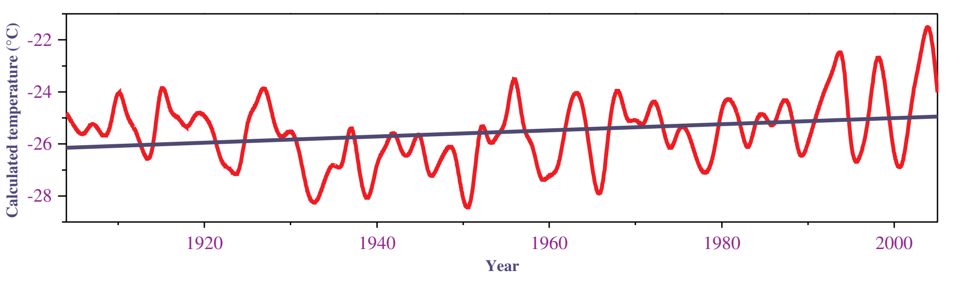
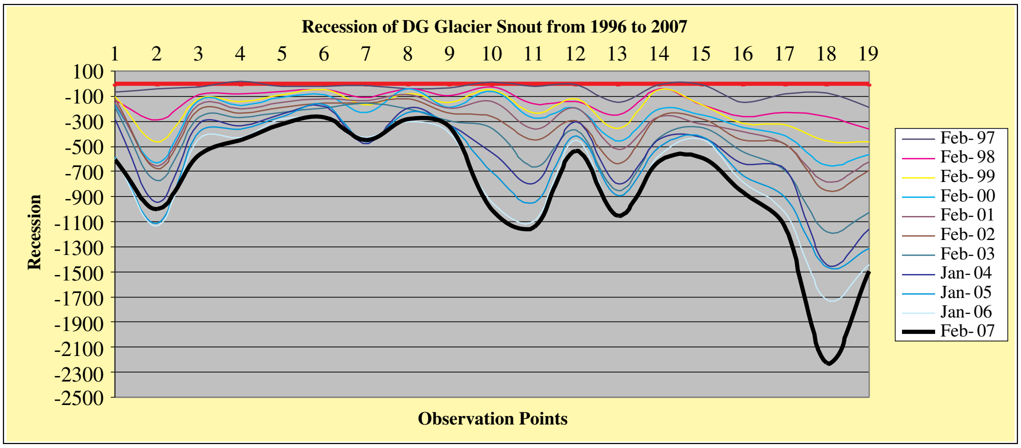


Figure 6: Recession of the Dakshin Gangotri glacier in Antarctica.



Larsemann Hills area include geological mapping, geotechnical investigations, characterization of different features of polar ice, snow sampling, monitoring of surface ozone, aerosol distribution, environmental data collection, and biological data collection.

Himadri, the Arctic station was set up in 2007. Short expeditions of up to 4–6 weeks are sent to Himadri. Glacier monitoring, microbial studies and atmospheric studies are the highlights of this program.

An ice-core laboratory has been set up to serve as a repository of cores both from Antarctica and the Himalayas. This is being used to infer past climate and environmental changes and will help scientists to refine climate models.

The Southern Ocean cruises focus on biogeochemistry and living resources. These multi-institutional expeditions are looking to fill the gaps in scientific information related to biogeochemical changes in carbonate/silicate chemistry. Studies are concentrated on looking for sedimentary evidence/present day structure and how the biological pump operated during glacial episodes.

8. Coastal and marine ecosystems

Human activities, natural hazards and the effects of climate change, viz. increase in sea surface temperature, sea level rise and ocean acidification affect coastal and marine ecosystems. The focus is on understanding the structure, function and vulnerability of ecosystems. We need to ensure a healthy oceanic environment for the benefit of successive generations. Ultimately, ecosystem-based models to assess the impact of human activities including those of climate change and ocean fertilization will be developed. Some of the major achievements are given below.

i. An atlas on the distributional pattern of marine mammals, zooplankton, and seasonal climatology and productive patterns on the Indian EEZ has been prepared.
ii. Establishment of the Indian Ocean Biogeographical Information System (IndoBIS).
iii. GIS-based Information System on the marine benthos of the Indian Shelf areas of the west coast of India.
iv. The recent increased occurrences of harmful algal blooms is being investigated. The dynamics of *Noctiluca* blooms recurring along the NW coast during the late winter monsoon/early spring intermonsoon has been worked out.
v. Regular monitoring of marine pollution at 76 locations including 13 intense hotspots has been undertaken since 1992. It was observed that coastal waters beyond two km are clean except on the Mumbai coast.

9. Climate variability and change

This program addresses various scientific issues relating to climate change including the impact on sectors like health, agriculture and water. In an effort to explore and assess targeted science-facets of climate change that are highly relevant to the Indian region along with their global linkages, climate modeling and dynamics, regional aspects of global climate change using instrumental and proxy climate records, short-term and long-term climate diagnostics and prediction are some of the major programs that have been undertaken.

It has been observed that the increase in temperature over India is consistent with global data. The current decade has been one of the warmest during the last hundred years. The sea surface temperature has also increased. Argo floats provide data up to 2000 m and these also shows subsurface warming. The ocean has been absorbing excess heat and contributing to the sea level rise. Mountain glaciers and the snow cover have declined on an average in both hemispheres. The widespread decrease of ice and snow has contributed to the sea level rise. The sea level rise on the Indian coast was about 1.3 mm/year up to 2000. The rate of rise after 2004 is higher.

It is not very clear whether warming has any perceptible impact on rainfall. Precipitation is highly variable spatially and temporally. The frequency of heavy precipitation events has increased over most land areas consistent with warming and an observed increase of atmospheric water vapor. It has been that there are large uncertainties observed in emission scenarios, concentration scenarios and global climate models.

In view of this, the Indian climate program includes the following.

i. Improved monitoring of regional climate through increasing density of observation.
ii. Understanding the regional impact of climate change – particularly the monsoon system .
iii. Better quantification of physical processes relevant to the tropics –aerosol interaction, water vapour feedback, cloud interactions, etc.
iv. Developing reliable scenarios of climate change for India with uncertainty limits.
v. Develop better forecasting capability (offers improved capability to deal with adverse weather events and planning adaptation measures).

Climate products such as major anomalous climate event, high-resolution daily gridded rainfall data $(1° \times 1°)$ and $(0.5° \times 0.5°)$, high-resolution daily gridded temperature data $(1° \times 1°)$, and climatological summaries for districts and states have been generated.

10. Concluding remarks

A deeper understanding of the components of earth systems and will probably tell us how the earth is changing. Long-term measurements, both in situ and satellite are crucial to these aspects. An assessment of the variability of the Earth system and change, is expected to result in improved prediction of weather, climate and hazards. At the same time, we also need to build capacity in the area of scientific aspects of climate change research. The responsible stewardship of the Earth, as an integrated system, is an investment that will pay dividends for generations to come. Some of the following future programs being planned are expected to address these issues.

Monsoon mission: Development of a single forecasting system to forecast rainfall at various spatial and temporal scales.

Mountain meteorology: A Dense network of observing platforms especially for the Himalayas.

Climate change: Setting up a High Altitude Cloud Physics Laboratory, Ocean biogeochemistry of the Indian Ocean, Impact of climate change on coastal zone, Cryosphere Processes and Climate Change.

Earthquake research: Setting up of a lab in Koyna to observe and study earthquake processes.

Energy: Harnessing ocean thermal energy.

The success of the ecosystem-based approach depends not only on technology and infrastructure but on people, an education system that produces scientists and managers needed for implementing such an approach. We need to build effective communication with various stake-holders including policy-makers.

Acknowledgments

I am extremely grateful to my colleagues at the Earth System Science Organization for their input and intense discussions which greatly helped in preparing this manuscript.

Received 27 October 2010.

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